TastyFloats: A Contactless Food Delivery System

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ABSTRACT
We present two realizations of TastyFloats, a novel system that uses acoustic levitation to deliver food morsels to the users' tongue. To explore TastyFloats' associated design framework, we first address the technical challenges to successfully levitate and deliver different types of foods on the tongue. We then conduct a user study, assessing the effect of acoustic levitation on users' taste perception, comparing three basic taste stimuli (i.e., sweet, bitter and umami) and three volume sizes of droplets (5µL, 10µL and 20µL). Our results show that users perceive sweet and umami easily, even in minimal quantities, whereas bitter is the least detectable taste, despite its typical association with an unpleasant taste experience. Our results are a first step towards the creation of new culinary experiences and innovative gustatory interfaces.

Author Keywords
Taste; Acoustic Levitation; Food Delivery System; Taste Perception; Taste Experience; Food Interaction Design.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
From Anakin Skywalker trying to woo Amidala by floating a piece of pear into her mouth (*Star Wars: Episode II)* to the restaurant *Sublimotion* [46] offering food in hovering plates, levitation of food has sparked the imagination of designers, scientists, and chefs around the world. For instance, chef Fernando Canales at Etxanobe (Bilbao) [7] or Anthony Martin at Morimoto (New York) [33] serve dishes on top of a levitating plate. Furthermore, LevitatingX [56] sells magnetically levitated plates for culinary presentations. All these examples reiterate the underling fascination of chefs for innovative ideas to create novel taste experiences.

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However, in these examples, the food is placed on a levitating dish: it must be eaten using cutlery. In other words, they only consider the final presentation of the food and not the whole delivery chain from the kitchen to the customer: food preparation, transportation, and delivery.

Despite this increasing interest in levitating food, none of the current approaches can deliver food morsels directly from one location to another. Such a food delivery system could be valuable both for creating novel restaurant experiences and for designing new end-to-end gustatory interfaces. As a step in this direction, we introduce TastyFloats (see Figure 1), a contactless food delivery system that uses ultrasound to levitate, transport, and deliver liquids and solid 'tasty bits'.

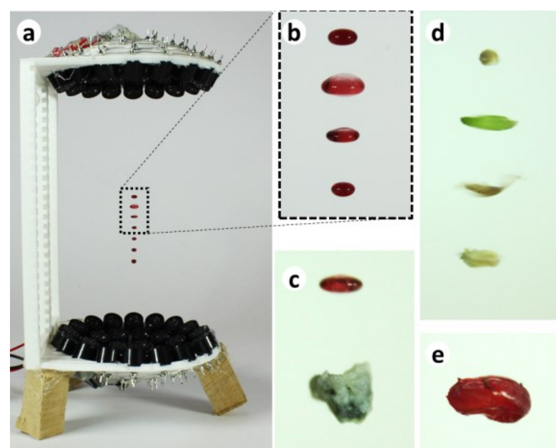

Figure 1. Examples of levitated food morsels: a, b) Acoustic levitation of droplets of wine; c) Wine and blue cheese; d) Bread, lettuce, meat and bread; e) and a raspberry grain.

Unlike magnetic levitation used in prior work (which required magnetic materials), ultrasound can levitate and hold in mid-air most substances. However, approaches based on acoustic levitation must overcome both technical and taste perception challenges to make them viable food delivery systems. For example, the device in Figure 1 could successfully levitate water or milk when powered with 18 Volts (peak to peak), but would evaporate ethanol (due to heating) or drop cheese (due to its heavier weight). A successful acoustic levitator has to dynamically adjust its acoustic energy to an appropriate value for the selected food.

In this paper, we first examine the acoustic parameters that govern levitated food such as the applied voltage, the food morsel's density and its exit velocity for targeting specific tongue regions. We then conduct a user study to compare the effect of levitation on user's taste perception accounting for various factors including the detection and discrimination of the taste stimuli, perceived intensity, pleasantness, and satisfaction. We finally discuss the relevance of our results, presenting an example implementation of the TastyFloats concept and how this informs the design of future explorations. For example, automated TastyFloats systems would allow sensorial augmentation in virtual reality and desktop gaming environments, as well as facilitate existing ideas such as Edible Cinema [8], where users enjoy little tasty bits during the narrative of a movie.

In summary, the contributions of this paper are threefold: First, we demonstrate how acoustic levitation can be used for levitating food in a controlled manner accounting for the system and food morsel characteristics in relation to user's taste perception. Second, we provide empirical insights on the effect of acoustic levitation on users' taste perception with the potential to transform today's molecular gastronomy sector [51]. Third, we provide designers and chefs with a framework to create novel gustatory experiences and interfaces not just for dining, but also for gaming, movie experiences, and interactive storytelling in VR.

RELATED WORK

Acoustic levitation

Levitation is the process of holding and moving an object in mid-air, without any mechanical support. The applications of contactless manipulation of objects in mid-air are very attractive and numerous, consequently different solutions have been proposed in the past: these are explored below, with the aim of finding the most appropriate one for food delivery, in both solid and liquid form.

Winborne et al. [55] achieved aerodynamic levitation of liquid metals using a nozzle-focused jet of air. His method, however, does not support low viscosity liquids (e.g., water). Also, if the air jet from the delivery system points toward the users it will cause major disturbances. Another approach is magnetic levitation that allows levitating a sample within a fixed distance from an electromagnet [39]. This approach has been used in HCI to levitate and actuate a magnetic sphere (ZeroN [28]), and in food presentation by international chefs like Fernando Canales at Etxanobe (Bilbao) [7] to serve levitating ferromagnetic dishes on top of a magnetic plate. A less strong, but more stable variation is the Meisnner effect (or Quantum Lock) in which a magnet levitates above a superconductor. This technique has been used to present levitating dishes of a couple of centimetres (e.g., Anthony Martin at Morimoto - New York [33]). Diamagnetic levitation uses repulsion from magnets [16], but the effect is weaker and the materials are still limited.

A promising way of levitating food, alternative to the previously presented approaches, is acoustic levitation. Sound is a mechanical wave and as such it carries momentum that can push particles due to radiation forces. When the forces exerted on an object are strong enough and converge from all directions, the particles can be levitated [5]. Usually, a single-axis levitator is used, composed of an emitter below and a reflector on top [53]. This setup creates a standing wave that levitates particles in the nodes and can suspend liquid droplets of up to half-wavelength diameter (4mm at 40kHz in air) [48]. Similar setups have levitated living insects [57], small fishes in a ball of water [47] and even small food items (e.g., [11, 27]). However, a complete food delivery system, including mid-air transportation and delivery to the end user, has not been attempted to date. Also, previous systems required high-voltage (>100V) that could be dangerous for the user.

Movement of the levitated particle can be achieved by changing the relative phase delay of multiple acoustic emitters, typically facing each other to create a standing wave. This method has been used before in HCI for creating mid-air crosses [35], floating particle displays [54], paths [36], charts [37] or to manipulate tiny particles with wearables [30]. Those systems typically require more powerful and cumbersome sound emitters [3, 15], like Langevin horns [2].

All considered, we believe acoustic levitation to be the most promising approach to levitate and transport a food morsel from one location to another, namely from the preparation area to the users' tongue. For doing so, it is important to account for the users' perception of specific taste stimuli.

Taste perception

Our taste perception starts at the human tongue which houses an average of 5,000 to 10,000 taste buds [40], which are activated by different taste stimuli (e.g., sugars, acids, salts). Experts in taste perception agree on five basic tastes [50]: sweet, sour, salty, bitter, and umami. These tastes can be perceived anywhere on the tongue. However, the human tongue is overall more sensitive around its edges (the tip and two sides), with the back of the tongue mainly sensitive to bitter to avoid swallowing poisonous substances [22].

In this paper, we focus on three of the five basic tastes: sweet, bitter, and umami. The sweet and bitter tastes are the two most salient sensory percepts for humans; sweet taste permits the identification of energy-rich nutrients while bitter warns against the intake of potentially noxious chemicals [38]. They are often referred to as the taste of reward (sweet) and punishment (bitter). This is because the aversive taste of bitter and the hedonic taste of sweet represent the two ends of the spectrum of taste perception, with sweet being perceived as pleasant and bitter as unpleasant [42].

Umami is the recent acknowledged basic taste and can be perceived as either pleasant or unpleasant, depending on the user's familiarity with it [34]. In addition, due to its flavour enhancing properties, umami is increasingly studied with respect to its effects on appetite and food [32]. As such, it provides an interesting third taste to be explored.

DESIGN PARAMETERS FOR LEVITATING FOOD

Levitation of solids and liquids has been shown using different set-ups, but it has not been considered from the perspective of food delivery. In a restaurant, food morsels need to be delivered in a hygienic, stable and repeatable way, as close as possible to how they come out of the kitchen. Food types of different densities and shapes will need different strengths to be delivered, so any food delivery system should be programmable and based on a solid theoretical background. Finally, the food morsel should be delivered where the user wants it: ideally directly on a specific position on the tongue and in a quantity sufficient to trigger a positive experience. Solutions based on Langevin horns have been excluded in this study, firstly because they would require high-voltage (which has safety implications) and secondly because the performance of these transducers is very sensitive to temperature changes (and thus they require stabilisation using feedback control loops). Here, we decided to use phased arrays instead, with the further constraint of using low-cost sound emitters. We show that using this technology it is possible not only to levitate liquids and pieces of food, but to deliver them to the tongue.

In the rest of this section, we discuss the different design parameters of a food delivery system employing the principles of acoustic levitation. We focus on two aspects: the transportation of the food morsels and their delivery. For the transportation, we consider parameters such as food material, density, size and viscosity, but discuss also other factors like temperature changes, evaporation, and potential spillage. For delivery we explore a gravity-driven solution, considering how parameters like the velocity of the morsel at the exit point of the transportation unit, its size, distance, and height with respect to the user's tongue impact on where the food morsels will land on the tongue.

Acoustic forces inside the delivery unit

To levitate a food morsel, the acoustophoretic force F_{rad} needs to exceed its weight. In air, a spherical particle smaller than the wavelength, experiences a force given by the Gor'kov model [6]:

$$F_{\mathrm{rad}} = -4\pi a^3 \left(\frac{1-\tilde{\kappa}}{3}\kappa_{\mathrm{a}}\langle p_{\mathrm{in}}^2\rangle - \frac{1}{2}\frac{\tilde{\rho}-1}{2\tilde{\rho}+1}\rho_{\mathrm{a}}\langle v_{\mathrm{in}}^2\rangle\right) \quad (1)$$

where a is the particle radius, p_{in} and v_{in} are the pressure and the velocity in air due to the emitted acoustic wave, $\tilde{\kappa} = \kappa_{\mathrm{p}}/\kappa_{\mathrm{a}}$ is the ratio between the compressibility of the levitated morsel (κ_{p}) and the air (κ_{a}) and $\tilde{\rho} = \rho_{\mathrm{p}}/\rho_{\mathrm{a}}$ is the ratio of their densities. In the simple case of a one-dimensional sinusoidal standing wave in the z direction, Equation 1 gives:

$$F_{\mathrm{rad}} = \frac{4}{3}\pi\Phi(\tilde{\kappa},\tilde{\rho})ka^3\frac{p_a^2}{4\rho_{\mathrm{a}}c_{\mathrm{a}}^2}\sin(2kz) \quad (2)$$

where p_a is the acoustic pressure (proportional to the voltage applied on the transducers), $c_{\mathrm{a}} = 343\mathrm{ms}^{-1}$ is the speed of sound in air at 20^0C, λ is the wavelength (8.6 mm at 40 kHz in air), $k = \frac{2\pi}{\lambda}$ is the wavenumber and $\Phi = \frac{5\tilde{\rho}-2}{2\tilde{\rho}+1} - \tilde{\kappa}$ the acoustophoretic contrast factor.Since the density of any solid/liquid morsel is much greater than that of air, $\tilde{\rho} \gg 1$ and $\tilde{\kappa} = \frac{1}{\tilde{\rho}}\cdot\frac{c_{\mathrm{a}}^2}{c_{\mathrm{l}}^2} \ll 1$, this case leads to a contrast factor, $\Phi = 5/2$, which does not depend on the levitated material. The minimum acoustic pressure to levitate a solid/liquid morsel of density ρ_{l} becomes ($g = 9.81\ \mathrm{m\ s^{-2}}$ is the local gravity):

$$p_{\mathrm{min}}^2 = \frac{8}{5}\frac{\rho_{\mathrm{a}}c_{\mathrm{a}}^2}{k}\rho_{\mathrm{l}}g \quad (3)$$

Spherical food morsels smaller than the wavelength can then be levitated by applying an appropriate voltage to the transducers, which only depends on their density (see FAO database for different food densities [13]).

As food morsels get bigger, other effects need to be considered: thermo-viscous effects may interfere with how food interacts with the acoustic field [25] and, depending on their surface tension, droplets can take non-spherical shapes at equilibrium (e.g. oblate ellipsoids [9]) or even become atomised by the levitator. In addition, the morsel may be heated during the delivery process, and increased temperature may cause evaporation or affect the taste.

To understand the impact of these phenomena, we focus the rest of our discussion (and the experiments) on liquid droplets, which are more susceptible to these effects. In particular, in the rest of this section we explore the case of 5 μL droplets for four different liquids: water, milk, ethanol, and wine (i.e. mainly a mixture of water and ethanol) [49]

- The four liquids have the same acoustophoretic contrast factor in air (within 1%), even when thermos-viscous effects are considered [25], what happens inside a droplet does not change the acoustic pressure to levitate it.
- Once levitated, however, the four droplets will have a different equilibrium shape. We describe them as two oblate semi-spheroids with a common semi-major axis L and two minor semi-axes b_1 and b_2 so that [9]:

  $$\frac{b_1+b_2}{2L} \equiv \xi(Eo) = \frac{1}{1+0.18\cdot(Eo-0.4)^{0.8}} \quad (4)$$

  $$\frac{a}{L} = \left(\frac{b_1+b_2}{2L}\right)^{1/3} \quad (5)$$

  where the non-dimensional parameter $Eo = 4g\rho_{\mathrm{l}}a^2\sigma^{-1}$ is known as the Eötvos number, $a = \frac{1}{2}\left(\frac{6V}{\pi}\right)^{1/3}$ is radius of the sphere with the same volume V and σ is the surface tension of the liquid in air. Equation (4) predicts milk droplets (E_o = 0.9for a 5 μL droplet) to be more spherical than the equivalent droplets of water or ethanol (E_o = 1.5 and E_o = 1.6, respectively).
- For a given liquid, deformation introduces a small dependence on volume in equation (3): larger pressures are needed to levitate larger droplets. At the first order, this can be considered by multiplying the RHS of equation (3) by the correction factor $\xi^{-1}(Eo)$.

- Applying an acoustic pressure to the droplet increases its temperature and evaporation. Ethanol is the most sensitive here, as it both requires less energy to vaporize (specific heat of evaporation: 38.6 kJ/mol compared to 40.6 kJ/mol of water/milk) and boils earlier (78.2ºC, compared to 100ºC of water and 100.2ºC of milk). Shiffer [41] reports the case of a droplet of ethanol levitated at 58 kHz evaporated completely in 200 s, while its water counterpart lasted >1000 s.
- When the acoustic pressure matches the pressure drop due to surface tension (i.e. $\sim\sigma/a$), instabilities at the interface lead to surface oscillations and eventually to the break-up and atomisation of droplets.

In summary, the voltage to apply may also depend on other properties of the morsel (e.g. its volume): a consideration that need to translate into practical operating choices, to be interpreted by the control software.

Release of the food morsel from the transportation unit

The motion of a food morsel once it is released from the transportation unit, depends on its output velocity v_0, on its mass, on the acceleration of gravity and on the viscous drag in air. The velocity of a morsel falling in air and starting with a velocity v_0 parallel to the ground is described by:

$$\dot{x}(t) = \frac{v_0}{1+v_0 t/H} \quad (6); \qquad \dot{y}(t) = U_T - \frac{2U_T}{\exp\left(-\frac{2U_T t}{H}\right)+1} \quad (7)$$

where H and U_T are a reference distance and velocity (see below), C_D is the drag coefficient, a is the volumetric radius, ρ_l and ρ_a are the densities of food and air, g is the acceleration of gravity, A is the area perpendicular to the direction of motion (πa^2, in the case of a sphere). Equation (7) means that, after falling for a distance H, an ellipsoidal droplet will reach a terminal velocity U_T. From (4) and (5):

$$H = 8\,a/(3C_D)\cdot\ \rho_\mathrm{l}/\rho_\mathrm{a}\cdot\xi^{2/3} \qquad (8)$$

$$U_\mathrm{T}^2 = \frac{8a(\rho_\mathrm{l}-\rho_a)g}{3\rho_a C_D}\,\xi^{2/3} \qquad (9)$$

Regarding the drag coefficient while objects smaller than 0.5 mm in air follow Stokes law [20], semi-empirical correlations are needed for larger objects/droplets. For the case of liquid droplets, Clift *et al.* [9] propose the following correlation, obtained by fitting data from different works:

$$\begin{cases} Re_T = 1.62\,Eo^{0.755}Mo^{-0.25} & 0.5 < Eo < 1.84 \\ Re_T = 1.83\,Eo^{0.555}Mo^{-0.25} & 1.84 < Eo < 5.0 \\ Re_T = 2.0Eo^{0.5}Mo^{-0.25} & Eo > 5.0 \end{cases} \qquad (10)$$

Equation (10) gives directly the terminal velocity in a non-dimensional format, as a function of the Eötvos number, $Re_T = 2\rho_a a U_T/\mu$ (Reynolds number) and $Mo = g\,\mu_a^4(\rho_l - \rho_a)/\rho_a^2\sigma^3$ (Morton number).

For a 5µL droplet of water/milk/wine, equations (8), (9) and (10) give velocities of 7-8 m/s and distances 20cm <*H*<30cm. Inserting these parameters in equations (6) and (7) gives control on the delivery of the food morsel after it exits the transportation system. Sufficiently below the transportation unit it will be possible to control the impact position on the receiving tongue only through the output velocity v_0 and the lateral position in the transportation unit.

Designing a software controller

Based on the above technical parameters, a customer could now choose a type of food to be levitated to a specific position on their mouth. The control software will accordingly (as in Figure 2):

- Measure the ambient temperature, to calculate density and viscosity of air.

- Based on the user input and an internal database, obtain the density of the food to be levitated.

- Calculate the acoustic pressure needed (Equation 3) and apply the appropriate voltage to the transducers, considering potential deformations for a liquid morsel (Equations 4, 5).

- Calculate the path and output speed required to deliver the morsel, so that it will land on the desired location of the user tongue (given the height and distance between the system and the user's tongue) – Equations 6 and 7.

- Calculate the number of food morsels to be delivered and their rate of preparation to produce a specific sensory experience. With the voltage that the transducers can sustain limiting density (Equation 3) and size (volume corrections) and the output velocity determined by the delivery point, it may be necessary to deliver multiple droplets of higher density morsels to achieve the same gustatory effect.

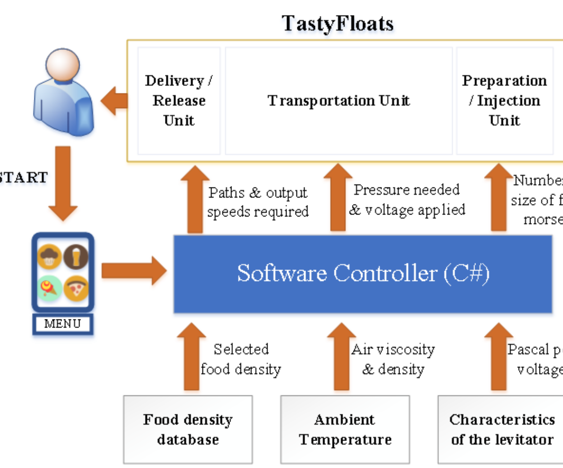

Figure 2. System architecture of TastyFloats where a user selects a food item. The software controller will determine the correct control parameters taking into account other inputs.

The set-up used for the perception studies (see below), for instance, operated at 40 kHz and generated 126 Pa/Vpp in the centre of the levitator. Here we managed to levitate 5µL droplets of ethanol ($\rho = 790\ \mathrm{kg\ m^{-3}}$) with 12 Vpp, while at least 13 Vpp were necessary for milk ($\rho = 1035\ \mathrm{kg\ m^{-3}}$) and 14 Vpp for water ($\rho = 1000\ \mathrm{kg\ m^{-3}}$), confirming that while the minimum pressure is mainly dependent on density (see Equation 3) – there is a minimal effect of shape. The difference in surface tension explains why 5μL droplets of ethanol ($\sigma = 22$ mN/m) burst at 14 Vpp, while water droplets of the same volume ($\sigma = 33$ mN/m) reached 18 Vpp before bursting. In these hypotheses, the fact that no bursting was observed with milk up to 20 Vpp indicates that the acoustic pressure was always much lower than the corresponding surface tension ($\sigma = 51$ mN/m). Finally, we observed that the volume of ethanol droplets clearly decreased with time while being levitated.

Since the transducers could support up to 20 Vpp in our TastyFloats implementation, delivering 40 μL of water could be achieved either with four 10 μL droplets at 15 Vpp or with two 20 μL at 16 Vpp. The possibility of adjusting the speed of translation or transporting different morsels simultaneously (like in a conveyor belt) allowed a constant flow rate of food towards the user.

TASTE EXPERIMENT

Prior research in experimental psychology and food science has shown that changes in the presentation of food and the environment change the taste perception of users [21]. Hence it was important for us to understand and assess the effect of using acoustic levitation on users' taste perception. We designed an experiment, where participants were presented with food morsels of different volumes comparing a levitation versus non-levitation (pipette) condition.

Study design

We conducted a 3x3x2 within-subject experiment in a counter-balanced order, comparing: **3 basic tastes** (sweet, umami, bitter); **3 volume sizes** (5μL, 10μL and 20μL); and **2 delivery mechanism** (levitation, pipette)

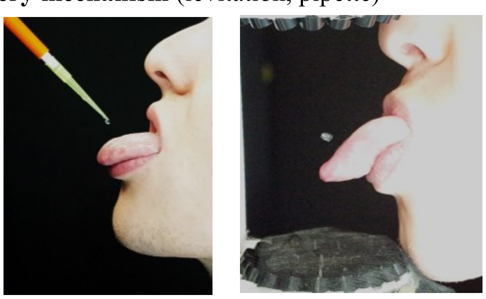

Figure 3. A participant getting a droplet of basic taste in the Pipette condition (left) and Levitation condition (right).

As discussed earlier, the applied acoustic forces on a droplet may change its temperature and evaporation, leading to its change in intensity, and consequently pleasantness and satisfaction of taste. Therefore, we use these three dependent variables (intensity, pleasantness, and satisfaction) to measure user taste perception of each droplet.

In total, each participant completed 54 trials (27 in each condition: 3 repetitions of 3 basic tastes x 3 volumes). Participants were asked not to eat spicy food, drink coffee, or smoke one hour before taking part in the experiment to avoid any bias of strong flavours on the taste perception [34]. The experiment lasted one hour in total.

Taste stimuli

Our experiment used three of the five basic tastes: sweet, bitter, and umami. The rationale of their usage is explained in our Related Work (see section on Taste Perception). Each stimulus was prepared as an odourless and colourless water solution as in [23]. The stimuli chemicals and concentration thresholds follow the specifications of prior works: sweet in the form of sucrose (at 75.31 mg/mL) [18], bitter in the form of caffeine (at 0.97mg/mL) [18], and umami in the form of L-Glutamate acid monosodium salt (at 8.46mg/mL) [26].

Taste stimuli volume

The basic taste stimuli were given to participants in the form of droplets. Three droplet volumes were chosen, due to the capability of the current prototype: 5μL, 10μL and 20μL. The tastes and volumes were randomized using a Latin square design to avoid any order bias [52].

To establish a baseline measure for the three taste stimuli, we also presented participants with three 25mL plastic cups filled with 2mL of each taste stimulus at the beginning and at the end of the experiment. This was important to account for any changes in their taste perception over time.

Levitation and pipette condition

We compared user's taste perception of basic taste stimuli in two conditions: levitation and non-levitation (pipette).

For the *levitation condition,* we used a static TastyFloats system: a single-axis static levitator (Figure 1), composed of 72 transducers placed on a pair of spherical caps, achieving a natural focusing at the center, so that the system can be driven by a single electrical signal. Pressure measurements confirmed that acoustic forces, numerically predicted using Equation 1, are null at the trapping point (middle) and otherwise converge towards it. Since the safety guidelines for devices using ultrasound in air are highly controversial [29], we decided to limit the electric power to the transducers in a conservative way – ALARP principle [12] – so that the peak acoustic pressure is 166 dB in the centre of the levitator (at 40 kHz, so not audible) and 133 dB at the ear of the user, i.e. below the most used threshold at 40 kHz [1]. The levitator can then operate with voltages up to 20 Vpp and currents up to 600 mA. This is within the safety guidelines for wearable devices that states that devices should not surpass 35V. Participants were asked to get the taste stimulus levitating in front of them with their tongue (Figure 3 right).

In the *pipette condition,* the stimuli were administrated to the participant's tongue using a micropipette, which was mounted at a fixed position, with the tip 2-3cm above the participant's tongue (Figure 3 left). The micropipette was manually controlled by the experimenter, which was the same across all participants to ensure the same procedure.

Procedure

Eleven participants (7 males, 4 females, mean age 30.18 ± 4.85) volunteered for this experiment. Upon arrival, the two delivery mechanisms (levitation and pipette) were covered and would only be revealed when the respective condition started. Participants read the Information Sheet and signed the Consent Form before participating. They were first presented with three 25mL cups filled with 2mL of each taste stimulus of three basic tastes (sweet, bitter, or umami) to rinse and swallow. After ingesting each cup, participants were asked to answer three questions and then rinse their mouth with water: ***(Q1)*** What taste did you perceive? - *Sweet / Bitter / Umami / Not sure*. ***(Q2)*** How intense was this stimulus? – using the Labelled Magnitude Scale (LMS) for taste perception [17]: *0-100 point scale* ***(Q3)*** How pleasant was this stimulus? – using the Self-Assessment Manikin (SAM) scale [4]: *9-point valence scale (pleasant/unpleasant).*

In each delivery condition (Levitation/Pipette), participants had 3 trials to practice and familiarize themselves with the delivery mechanism. Once confirmed that they were ready to start, participants completed a block consisting of 27 trials with 3 basic tastes and 3 volumes in a counterbalanced order.

Data collection

Each trial started by injecting the desired quantity of liquid in the micropipette, which was then used to either deliver the stimulus directly or to insert it in the levitator. The levitator was powered at 16Vpp, which was established as optimal value for levitating droplets between 5μL and 20μL (see previously calculated parameters for acoustic levitation). Participants were asked to turn away and did not see this procedure, to avoid any potential guessing of the upcoming taste or volume. Participants were then told to turn back.

After each trial, participants were asked if they perceived the taste stimulus. If yes, they were asked to answer questions ***(Q1)***, ***(Q2)***, and ***(Q3)*** and the additional question: ***(Q4)*** How satisfying was the taste stimulus? – using a 7-point Likert scale from *1/not satisfying all* to *7/very satisfying*. Before starting with the next trial, participants were asked to rinse their mouth with water to avoid any contamination of the next stimulus. At the end of each condition (after a block of 27 trials), participants were asked to rate their liking of the respective delivery mechanism on a 7-point Likert scale from *1/didn't like it at all* to *7/I liked it a lot*. Upon completion of both conditions (a total of 54 trials), participants completed a final questionnaire about age and gender.

RESULTS

Overall, we collected a total of 594 trials across both conditions for eleven participants. We used a multivariate ANOVAs with repeated measure design to analyze the data.

Liking of condition: First we established the liking of the levitation approach. Paired t-test of the two conditions showed that participants significantly preferred the levitation condition over the pipette (t_{20}=-4.23, p<0.001).

Taste recognized: Participants recognized the taste stimuli 68.56% correctly across both conditions with sweet taste was recognized with 86.36%, then umami with 70.41%, and surprisingly bitter was the least recognized taste with only 45.56%, even when it was selected as the aversive/ unpleasant taste. In specific for Levitation, participants recognized 64.95% correctly (sweet: 86.73%, umami: 64.95%, and bitter: 48.81%). For Pipette condition, they recognized 69.26% correctly (sweet: 85.86%, umami: 75.76%, and bitter: 42.35%).

Intensity: Paired t-test found significant differences between the two conditions with respect to the perceived intensity (t_{279}=2.58, p<0.05). The perceived intensity is significantly higher in the levitation condition (M=16.02, SE=0.85) compared to the pipette condition (M=13.57, SE=0.78). Figure 4 shows the perceived intensity for both conditions and for each taste. When performing a pairwise comparison of intensity within each condition we found no significant difference between the sweet and umami taste, but significant differences between bitter and the two other tastes ($F_{2,11452}$=34.74, p<0.001 for levitation and $F_{2,4746}$=33.22, p<0.001 for pipette). Additionally, we could not find significant differences between the two conditions in intensity of each individual taste (p>0.05).

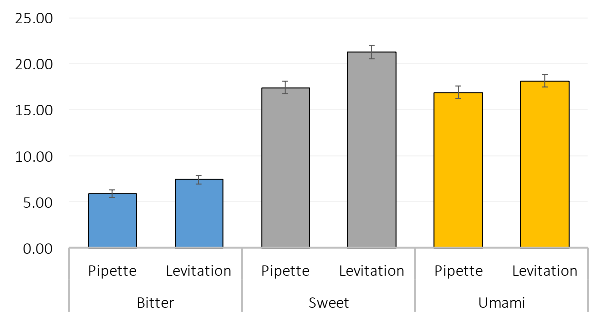

Figure 4. Perceived taste intensity for all three tastes (bitter, sweet, and umami) in both conditions.

Pleasantness: The baseline ratings confirm sweet and bitter were at the two extreme ends of the pleasantness scale, and umami was rated in between. Specifically, the baseline rating of sweet was M=7.0 (SE=0.33) on the 9-point SAM scale, bitter M=3.0 (SE=0.39), and umami M=4.48 (SE=0.57).

Condition	Taste	Pleasantness	Satisfaction
Pipette	*Sweet*	6.22 (SE 0.12)	4.47 (SE 0.12)
	Bitter	4.76 (SE 0.09)	3.32 (SE 0.11)
	Umami	5.02 (SE 0.13)	3.41 (SE 0.13)
Levitation	*Sweet*	6.45 (SE 0.11)	4.89 (SE 0.10)
	Bitter	4.55 (SE 0.08)	3.24 (SE 0.09)
	Umami	4.84 (SE 0.15)	3.60 (SE 0.13)

Table 1. Perceived plesantness and satisfaction ratings for both contions accounting for all three taste stimuli.

Across both conditions, the pleasantness of sweet (M=6.34 SE=0.08) was lower than the baseline scores. Surprisingly, bitter (M=4.66 SE=0.06) was rated pleasant compared to its baseline ratings, considering that bitter was recognized correctly 45.56% of the time. Umami (M=4.93 SE=0.10) was rated similarly to the baseline ratings, supporting the hypothesis posed by sensory scientists that the perception of umami is not affected by external factors [44]. There was no change in the pleasantness ratings over time (p>0.05) (see Table 1 for more details of the pleasantness ratings).

Satisfaction: Similarly, the satisfaction ratings across both conditions show that sweet was perceived as slightly satisfying (M=4.68 SE=0.08) while bitter (M=3.28 SE=0.07) and umami (M=3.51 SE=0.09) were perceived as slightly unsatisfying. Table 1 shows an overview on the participants' satisfaction ratings for each taste in each condition. Paired t-tests of pleasantness between the two conditions found no significant difference (p=0.74). Similarly, we found no significant differences between the two conditions with respect to the perceived satisfaction (p=0.05).

Finally, to assess the influence of the droplet volume, we performed Pearson correlation tests between the four factors: intensity, pleasantness, satisfaction, and droplet volumes, across tastes and the two conditions using Bivariate function in SPSS. The output was cross-correlations for each pair of two variables. We found that participants perceived intensity accordingly to the taste volume (r=0.22, p<0.001). In other words, the bigger the stimulus volume, the more intense participants perceived. Their perceived pleasantness and satisfaction significantly correlated with the intensity (p<0.001). For sweet, the volume size significantly correlated with the perceived intensity (r=0.25, p<0.001), pleasantness ratings (r=0.225, p<0.005), and satisfaction (r=0.21, p<0.005). We did not find any significant correlations for bitter. For umami, the volume only influenced the perceived intensity (r=0.34, p<0.001) but neither pleasantness (p=0.68) nor satisfaction (p=0.75).

Summary

With the limitations described later, our results show that the taste perception (recognition rates) in the levitation condition is highest with sweet, followed up by umami taste. Surprisingly, the bitter taste is the least detectable taste stimulus, but at the same time also perceived as slightly pleasant despite its traditional aversive nature. This is intriguing from a food-interaction design perspective. For example, if one would want to levitate bitter food morsels (e.g., coffee) a higher intensity would be required to ensure recognition and satisfaction. In contrast, the sweet taste is the most stable and would allow food delivery with a consistent detection, pleasantness and satisfaction rate. Moreover, our results also confirm that users can perceive and enjoy even the smallest morsels (5µL, 10µL and 20µL) without negative impact on the user satisfaction. Taken together, this are promising results that first of all confirm the perceivability of levitated food morsels by end users, and additionally open up clear directions for future studies on the hedonic qualities of taste stimuli (to what extend can acoustic levitation be used to modulate the pleasantness of a stimulus).

DISCUSSION AND DESIGN POSSIBILITIES

Based on the investigation of the technical and perceptual parameters of TastyFloats, we can now discuss the design possibilities. Below we provide designers and chefs in the realm of molecular gastronomy with a framework to create innovative food experiences and novel gustatory interfaces.

TastyFloats – A contactless food delivery concept

With emerging interest from molecular gastronomes in new food delivery systems and novel gustatory interfaces, there are several design opportunities for TastyFloats. Our main implementation of the TastyFloats concept (Figure 5) is an elongated, gazebo-shaped version of the static levitator used in the user study (Figure 1). As described in Figure 2, the control software for this unit consider food parameters (i.e., density, volume and shape of the selected food morsels) as well as other factors (e.g. temperature changes, evaporation and potential spillage) to calculate and apply the appropriate forces needed to transport the morsels. The main difference with the static unit is that, once captured in an acoustic standing wave at the start of the transportation unit, the food morsels are moved across the transportation unit by changing the acoustic field in the device [36] (see Supplementary Information – S-Figure 2 for its simulated amplitude field).

The transportation unit in Figure 5 consists of 132 ultrasonic transducers (Murata MA40S4S), four 4-channel Motor Drivers (L298N) used to amplify signals up to 35Vpp, and an Arduino Nano that generates up to 16 half-square signals at 40 kHz. The maximum voltage is, once again, limited by the transducer threshold and the guidelines in user safety.

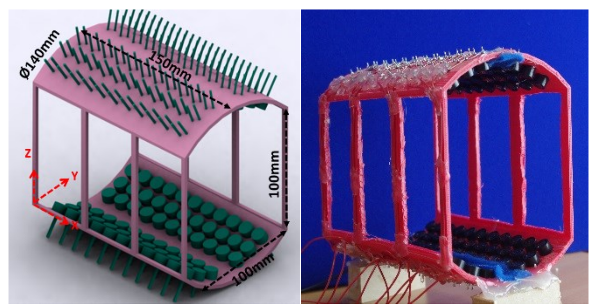

Figure 5. Schematic of the transportation unit (left) and implementation prototype (right). See the accompanying video for the direction of motion of the food morsels.

In each time interval Δt, the control software calculates the phases for the transducers using the holographic method [31], moving the trap in $\Delta X = 0.4$ mm steps along a pre-configured linear path along the central X-axis and sends them to the Arduino. Symmetries in the transportation unit were used to reduce the number of required signals: while the system has 132 transducers, they are arranged at the same distance from the central X-axis, so the same signal is used for each radial segment of transducers (11 in total). The dynamic standing wave generated by the transportation unit can accommodate several food morsels in the vertical Z direction, as the standing wave contains various nodes. The forces near each trapping position are similar to those of the static levitator (see Supplementary Information – S-Figure 1 for more characteristics details). Additionally, the software controls the time interval Δt, considering the requirements of the delivery unit where $v_0 = \Delta X / \Delta t$. For liquids, the range of possible values of v_0 is a compromise between the need to avoid evaporation of the food morsel (with a large Δt morsels spend more time in the transportation unit) and the need to minimise spillage during transportation (small values of ΔX produce shape oscillations in a levitated droplet).

Finally, food morsels are released at the other end of the transportation unit with an exit velocity $v_0 = \Delta X/\Delta t$. In the experiments, we observed that some levitated droplets exit the transportation unit while rotating (possibly due to small imperfections in the alignment of the transducers near the exit), so we decided to position the tongue where terminal conditions for the falling motion are achieved (Equation. 8 and 9). At a relative height H below the unit, the motion is only decided by the velocity v_0. This allows a functional separation between the production (i.e., in the kitchen) and the consumer at the end of the device, with TastyFloats' control software ensuring that the food morsels fall on the designated location on the user's tongue.

Tasty desserts vs. Tasteless coffee

It is nowadays accepted that the delivery context affects the taste perception. For instance, the humidity, air pressure and background noise in an airplane decrease our sensitivity to salty and sweet tastes, forcing chefs to add more salt to food [14]. Similarly, because of the high altitude, passengers appreciate added honey in their beer to overcome the heightened bitter taste [45]. In these contexts, umami may be the only basic taste that remains unaffected (e.g., by background noise in airplanes [44]).

The results of our user study show that the perceived intensity of levitated morsels is greater than the one of their non-levitated counterparts. This supports levitation as a successful delivery method. Results also show that, relatively to the small volumes delivered, sweet, bitter and umami are recognized differently. We found that, for a given volume, participants recognized the sweet taste almost every time (~85%), while they found bitter difficult to distinguish (~45%). That makes TastyFloats systems more suitable for presenting desserts rather than bitter tastes. In other words, to obtain a higher recognition of a given dish, the recipe used should be mainly around sweet stimuli (e.g. levitated marshmallows). Moreover, the fact that umami is recognized 70% of the times and is perceived to be more pleasant than expected – from studies involving larger quantities [32] – may open interesting opportunities in the dietary treatments, where umami-enriched food is key.

Our results suggest that TastyFloats can help customers to ingest bitter food but healthy benefits (e.g., broccoli), providing users with a less uncomfortable experience (e.g., encouraging the consumption of vegetables or fish oil for children). If we wanted to deliver bitter taste to willing customers instead (e.g., apéritifs and digestifs), a higher volume would need to be used to trigger a comparable experience to the non-levitation condition while keeping the same concentration. Otherwise, bitter food such as coffee would need to be made bitterer to be equally detectable and enjoyable in levitated conditions.

Applications towards novel gustatory interfaces

Levitation of food is relevant for the realm of food interaction design, an area of research that has gained increased attention in recent years [10, 19, 24]. In addition, chefs across the world have become increasingly fascinated by exploiting novel technologies, food presentation using levitation already appears in high-end Michelin star restaurants. If fully controlled, levitation has the potential to become a tool for molecular gastronomy, the branch of food science which investigates the physical and chemical transformation of minimal quantities and food ingredients to create innovative, surprising new experiences [51]. According to our results, TastyFloats can be readily applied to deliver molecular gastronomy inspired desserts that stimulate our taste palette with different types of sweetness.

Additionally, TastyFloats not only helps to change the way we experience food in the future, but also inspires and provides guidance on how to design novel end-to-end gustatory interfaces. For example, TastyFloats can change the manual approach in Edible Cinema [8], by integrating an end-to-end food delivery system in the back of a front-seat for the viewers to get time-synchronized food delivery in mid-air. Food items could even be labeled and delivered by the movie distributor, so that precise quantities of the food can be presented to the audience in line with the narrative of the movie. The audience can then decide whether to accept or ignore the proposed gustatory stimulus simply by leaning forward or back whenever they want. Similarly, in a desktop gaming environment, the TastyFloats framework can guide the design of multi-user levitation systems, where different stimuli represent reward or punishment. Alternatively, within the technical constraints, the rate of delivery can be changed depending, for instance, on the atmosphere of the game or the acquired skills/level of the character in a RPG.

From single to multiple food morsels

TastyFloats was demonstrated for levitating single food morsels but, as shown in the accompanying video, also provides the foundations to be expanded for multiple morsels. Complex food, such as the ingredients of a burger combining bread, meat, and lettuce (Figure 1d) can be easily levitated. We can specify and control the path of a set of ingredients (e.g., by adapting the system parameters to levitate the heavier one) and ensure that the food arrives on the customer's tongue in the chef's preferred fashion (e.g., first bread then meat). This opens the possibility of making recipes by mixing tastes directly on the tongue of the customer to create surprising experiences. Cinematographic examples in this direction can be found in the animation movie *Ratatouille*, when the main rat character mixes one morsel of cheese with one of mushroom to explore their combined taste. Acoustic manipulation has never been used for transporting food, and the possibility of using levitation to warm food as it is being transported enables new culinary experiences. Further user studies will need to investigate the complex interaction of flavor perception and smell [43], allowing multisensory approaches in taste experiences.

Limitations

This work presents a first step towards the design of a novel food transportation system based on the TastyFloats concept. Technically, we demonstrated for the first time the transportation of food morsels in mid-air where, to date, levitation is only used to hold food items in place (e.g., magnetic levitation). It can be argued that our demonstrator is slow, but we trust that the limitations in speed and quantity delivered through TastyFloats will soon be solved, as acoustic manipulation is a rapidly emerging technology (e.g. by close-loop systems for speeding up the transport). Recent studies, for instance, demonstrated acoustic levitation for objects much larger than the wavelength [3]. We have not demonstrated a delivery prototype, but we systematically presented and discussed whether it is possible to deliver discernible quantities of foods to different parts of the mouth, even with a simple gravity-driven system. Future implementations will investigate how the presence of the tongue affects the acoustic field and integrate algorithms to precisely locate the tongue during delivery.

Our user study was carried out with the single-axis levitator and not with the complete food transportation system: the active collection of the morsel may have had a role in the pleasantness of the experience. Moreover, the study was conducted with a reduced number of users and taste stimuli (liquid with a specific concentration). Still, we obtained interesting and insightful results: even if the food portions were small, they were sufficient to elicit in the user perception and discrimination between basic tastes. In future works we will expand the sample size of the participants and the number of taste stimuli, for a more comprehensive understanding of the effect of acoustic levitation on taste.

CONCLUSIONS

TastyFloats is a contactless food delivery system based on acoustic levitation and an innovative design framework that has the potential to transform future eating experiences as well as the design of novel gustatory interfaces. We demonstrated how to successfully levitate liquid and solid food morsels considering the system parameters, the ambient temperature, the characteristics of the food items, and its effect on taste perception. Our results show that users can perceive and effectively discriminate different taste stimuli. Most interestingly, we observed that the hedonic quality of the bitter taste is modulated in the levitation condition, making it a less unpleasant taste. This modulation allows chefs to experiment in the context of molecular gastronomy, but can also be a game-changer in food-interaction design for children (e.g., make eating vegetables more enjoyable). TastyFloats can also inspire new interactive experiences in gaming, VR, and be thought of as a contactless delivery system for medicine (e.g., for paralyzed users).

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